Final Technical Report

Improved Monitoring of Tremor, Earthquakes and Volcanoes by the PNSN with Methods to Search Continuous Waveforms

USGS Grant No. G09AP00024

PIs Kenneth C. Creager and John E. Vidale,
University of Washington

Along the northern Cascadia margin, GPS observations provide evidence of periodic, 2-week-long movements of plate motion between the subducting slab and overriding continental crust [Rogers and Dragert, 2003]. This slip event coincides with an emergent, enduring, and low-frequency signal know as tremor. From a hazards perspective, slow slip events are important in assessing risk associated with the updip seismogenic zone in two ways. First, it is thought that slip relieves stress locally while increasing stress on the locked zone with the potential to trigger a megathrust earthquake [*Dragert et al.*, 2001]. Second, spatially resolving slow slip could help map the freely-slipping, transition, and locked segments of the subducting Juan de Fuca plate relative to the dense urban centers along the fault margin. The other aspect of this episodic tremor and slip (ETS) phenomenon, tremor, could prove very useful in monitoring slow slip and understanding the parameters controlling it. Geodetic observations offer good macroscopic views of slow slip events; however, GPS detection of slip often occurs after or late-into the event with limited spatial and temporal resolution. Thus, establishing a link between tremor and slip enables the possibility of using tremor activity as a proxy for slow slip in time and space. Tremor monitoring can provide more timely slip recognition, and a tremor catalog enables higher-resolution estimates of where this stress loading—and hence triggering potential—may occur.

Using a previously developed autonomous method for detection and location of tectonic tremor [*Wech and Creager*, 2008], we have created a catalog of tremor activity across the Cascadia margin. Applying this technique to 7 overlapping networks (Figure 1) from northern California to mid-Vancouver Island on past and real-time data, we monitor both ETS and inter-ETS tremor activity starting from 2006. The resulting epicenters augment previous monitoring efforts in northern Washington to provide an unprecedented map of the Cascadia tremor source region (Figure 2), a new ability to investigate the role of inter-ETS tremor, and a basis for expanding realtime routine monitoring to the rest of the subduction zone.

We obtain 70,000+ tremor epicenters to map out the margin (Figure 2). We find that the tremor zone has an average width of 53 +/- 9 km and is generally bounded between the 30-45 km plate interface depth contours, with some deviation in the south. We also find a distinct updip edge whose boundary may represent a physical change in plate coupling that is 10's of km further inland than current estimates of the downdip edge of the seismogenic zone.

Using this catalog, we define a new class of event that encompasses the larger "ETS" events by searching for tremor that clusters in space and in time and call these events "tremor swarms" [*Wech et al.*, 2010]. In northern Washington (where we have the most consistent catalog) ETS events repeat every 15±2 months [*Miller et al.*, 2002; *Rogers and Dragert*, 2003]—except for May 2009—and are remarkably similar in duration, area, and moment. For each of these events, the tremor pattern is in strong agreement with geodetic slip patterns [*Wech et al.*, 2009]. From 2006 through 2009, we find 88 distinct tremor swarms including the three ETS events in January 2007, May 2008 and May. Inter-ETS tremor was detected in ~11000 windows, some of which overlap by 50%, so tremor was seen 2% of the time. The number of hours of tremor per smaller swarm ranged from about 1 to 68, totaling 746 hours. Theses smaller tremor swarms generally locate along the downdip side of the major ETS events, and account for approximately 45% of the time that tremor has been detected during the last three ETS cycles [*Wech and Creager*, 2008; *Wech et al.*, 2009]. Only the largest events coincide with geodetically observed slip, meaning that current geodetic observations may be missing nearly half of the total slip. Like the major ETS tremor swarms, many of the smaller events are near-carbon copies in duration, spatial extent and propagation direction.

These 50 inter-ETS swarms follow a power law relationship such that the number of swarms, N, exceeding duration τ is given by $N \sim \tau^{-0.7}$ [*Wech et al.*, 2010]. If we assume that seismic moment is proportional to τ as proposed by Ide et al. [*Ide et al.*, 2007], we find that the tremor swarms follow a standard Gutenberg-Richter logarithmic frequency-magnitude relation $N \sim 10^{-bMw}$ with b = 1.0 (Figure 3), which lies in the range for normal earthquake catalogs. If we include two most recent major ETS events in this analysis, we find that they also fall on the curve defined by the inter-ETS swarms (Figure 3) [*Wech et al.*, 2010], suggesting that the inter-ETS swarms are just smaller, more frequent versions of the major 15-month ETS events.

Finally, we have extended our system to automatically detect, locate and report tremor activity in near-real-time on an interactive webpage to the rest of the subduction zone [*Wech*, 2010]. This system expands on previous monitoring efforts in northern Washington. Once detected, tremor results flow to a website which draws on a combination of freely available API (application programming interface) products to provide an intuitive interactive user experience (Figure 4) [*Wech*, 2010]. Data from the several seismic networks stream into the Pacific Northwest Seismology Network's Seismology Lab. At the end of each GMT day, data from a preselected subset of ~100 of these incoming streams are broken into 7 overlapping regional sub-networks spanning from northern California to mid- Vancouver Island (Figure 1). For each region, the sub-network envelope data are used in the detection and location step. Completing in about 1 hour, daily results are available online around 18:30 PST. If any activity occurred along the margin, the system will also dispatch email alerts and text messages detailing tremor results for each active region. Once online, the results are manipulated using dynamic hypertext markup language to give the user full control to customize and view locations and time series, customize time ranges, customize regions, animate tremor activity, view seismic station geometry, and view data (Figure 4). Collectively the resulting product is an automatic margin-wide tremor catalog and a website disseminating this information in a way that is accessible and engaging to the general population yet remains valuable as a tool for scientific synergy across institutions and disciplines.

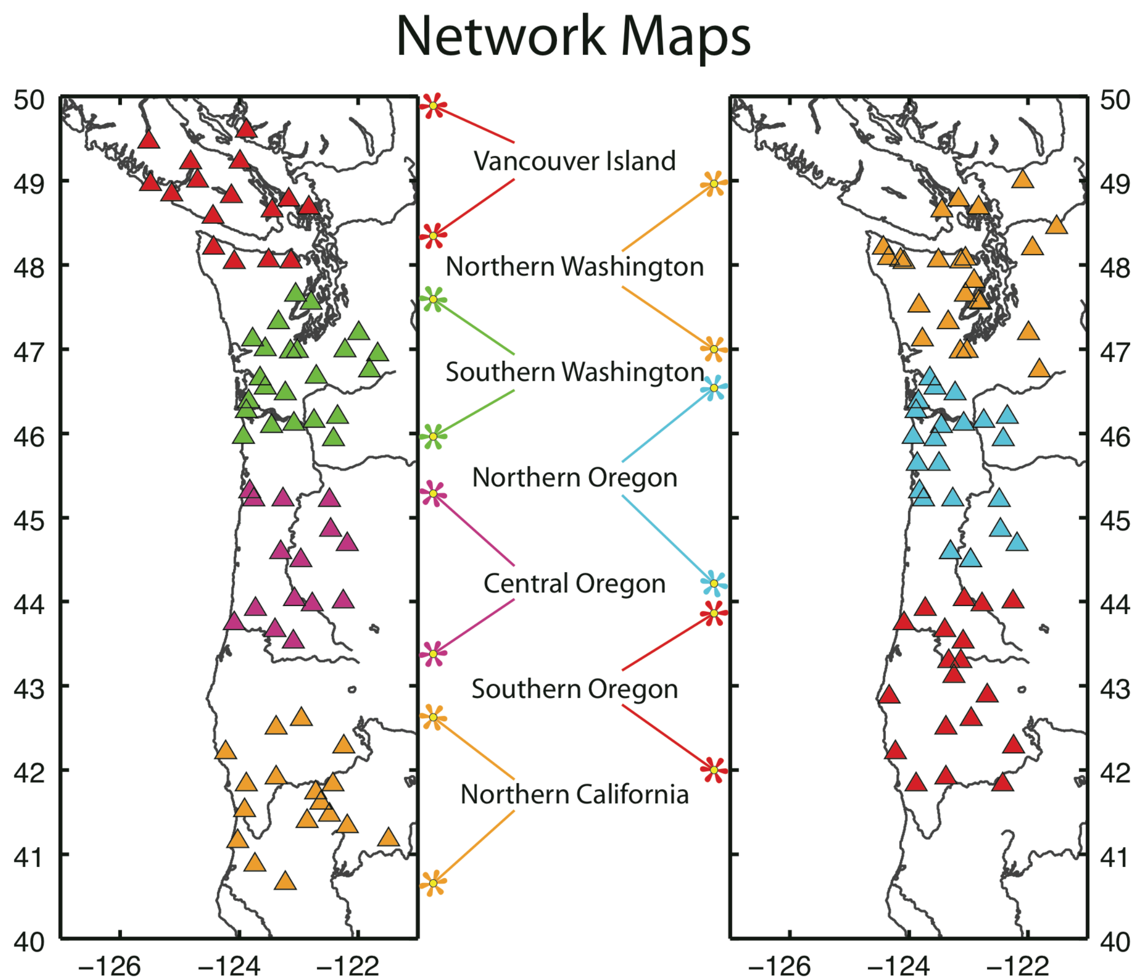

Figure 1. Station map for each of the seven overlapping networks.

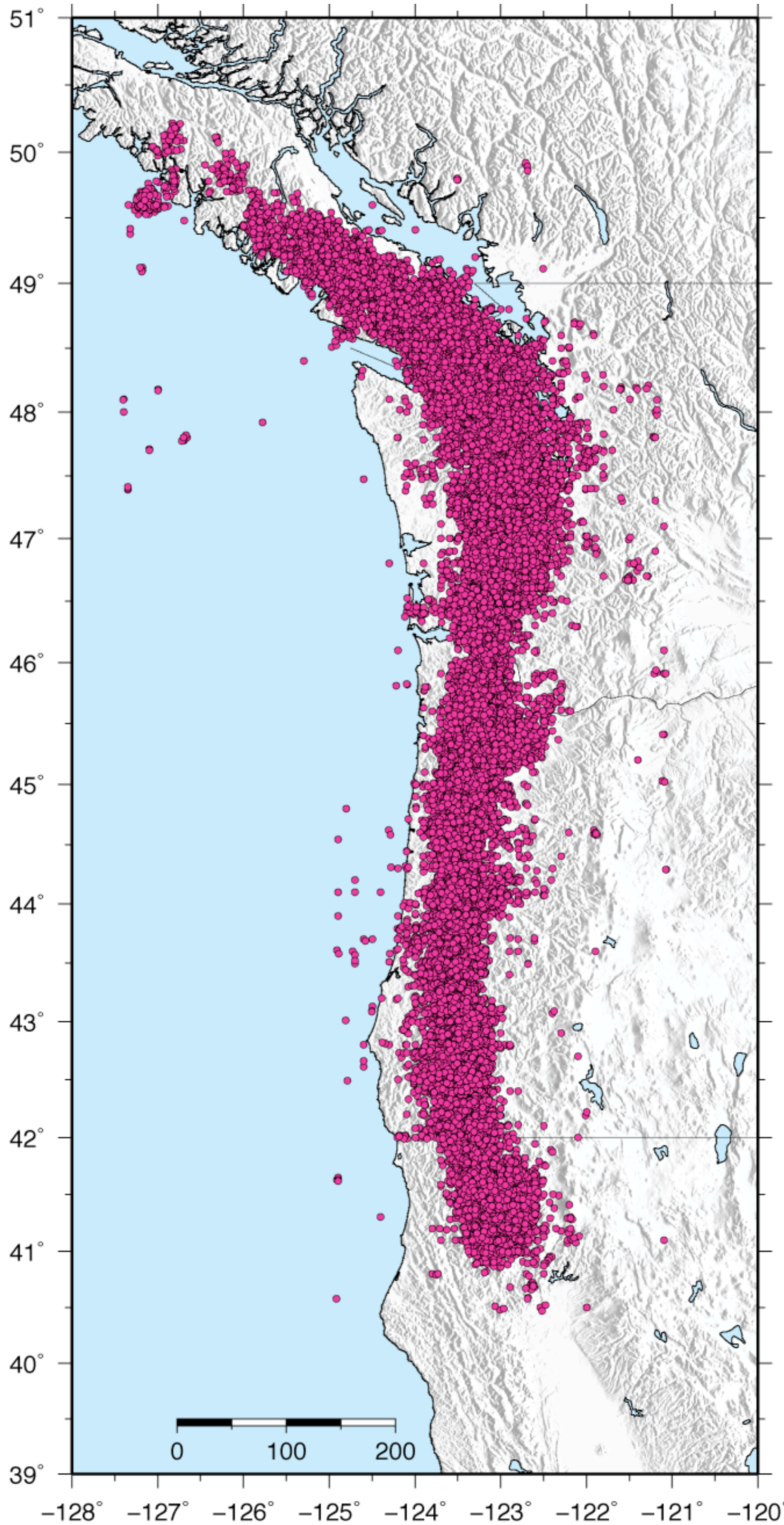

Figure 2. Results of automated detection and location efforts. ~70,000 epicenters.

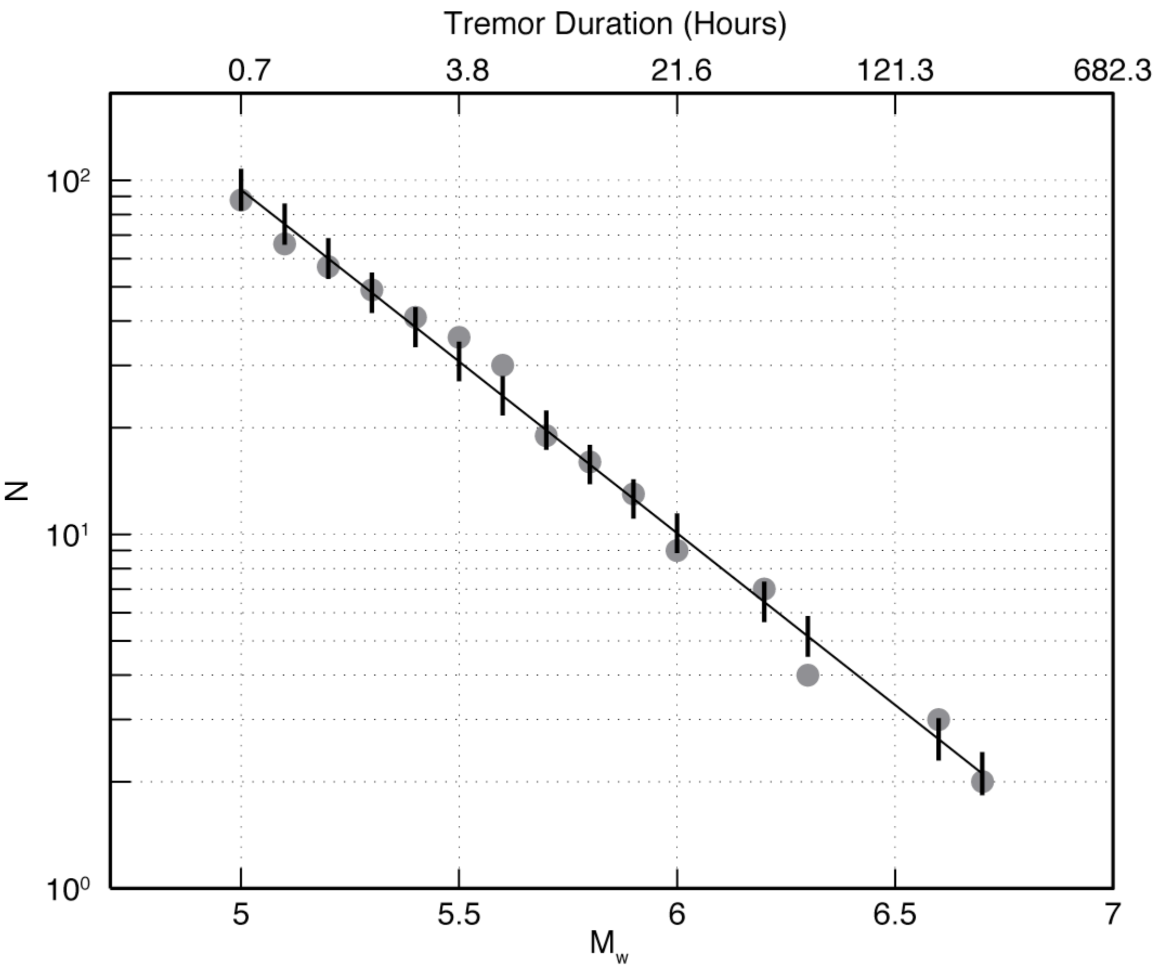

Figure 3. Log of number of tremor (*N*) swarms exceeding durations given on upper axis can be fit with a straight line indicating that *N* is proportional to $\tau^{-0.7}$ where τ is the duration of a tremor swarm. If we assume that the seismic moment is proportional to tremor duration at a rate of 5.2×10^{16} N-m/hr [*Aguiar et al.*, 2009; *Ide et al.*, 2007] we can equate duration to seismic moment (lower axis). This allows a standard Gutenberg-Richter style analysis and produces a b-value of 1.0 ($N = a10^{-bMw}$), which is within the range commonly seen for regular earthquakes.

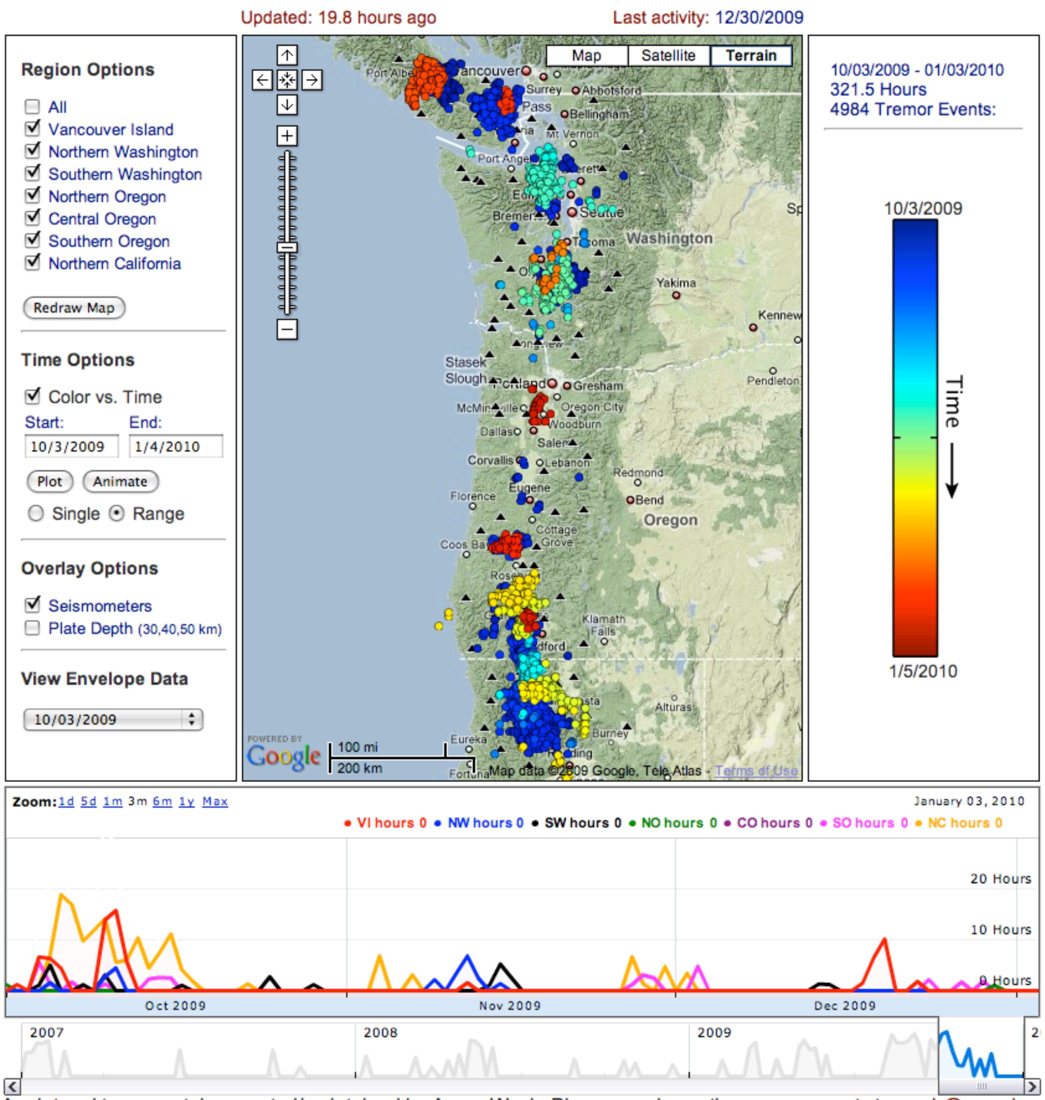

Figure 4. A screenshot of the web product resulting from this near realtime system. The left panel contains all of the interactive options. Here the user can choose which region and date range to look at. There is also the option of overlaying the station distribution on the map as well as the subducting plate depth contours. Locations may be uniform or color-coded with time. Single days or range of dates may be toggled. Clicking in the date text boxes triggers a dropdown calendar with active dates highlighted and summarized. The bottom panel shows a time series of tremor duration by day for the entire available time range (bottom) and zoomed in time range (top) with color-coded regional summaries following the cursor (top-right) and preset zoom options (top-left). Regional toggles change both the calendar and timeline while a date change in either adjusts the other. The right panel contains a summary of plotted info (top) and the colorbar (shown here) or event table if <1000 events are requested with no color-coding.
URL: www.pnsn.org/tremor

Aguiar, A. C., et al. (2009), Moment release rate of Cascadia tremor constrained by GPS, *Journal of Geophysical Research-Solid Earth*, *114*.

Ide, S., et al. (2007), A scaling law for slow earthquakes, *Nature*, *447, doi:10.1038/nature05780*, 76-79.

Miller, M. M., et al. (2002), Periodic slow earthquakes from the Cascadia subduction zone, *Science*, *295*, 2423.

Rogers, G., and H. Dragert (2003), Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip, *Science*, *300*, 1942-1943.

Wech, A.G., and K. C. Creager (2008), Automatic detection and location of Cascadia tremor, *Geophys. Res. Lett.*, 35, L20302.

Wech, A.G., K. C. Creager, T.I. Melbourne (2009), Seismic and geodetic constraints on Cascadia slow slip, *J. Geophys. Res, 114, doi:10.1029/2008JB006090.*

Wech, A.G. (2010), Automated monitoring and interactive web display of tremor activity in the Cascadia subduction zone, *accepted to SRL*.

Wech, A.G., K.C. Creager, H. Houston, J.E. Vidale (2010), The magnitude distribution of tremor in Northern Cascadia Episodic Tremor and Slip, *in preparation*.